Impacts of the Zonal Position of the East Asian Westerly Jet Core on Precipitation Distribution During Meiyu of China*

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ABSTRACT

The east-west location change of the East Asian westerly jet (EAWJ) at 200 hPa during Meiyu and the associated spatial distribution variation of precipitation in the middle-lower reaches of the Yangtze River (MLYR) are investigated by using the 40-yr NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) pentad mean reanalysis data and daily precipitation observation data from 1958 to 1997. The results show that there are two areas over which the 200-hPa EAWJ center appears most frequently during the Meiyu period: one is the western Pacific (WP) and the other is the East Asian continent (EAC). During the Meiyu period, the westerly jet over the EAC is weak, and the core of the westerly jet over the WP splits up with reduced intensity and disappears by the end of Meiyu. The changes in the location and intensity of the westerly jet are associated not only with the starting and ending dates of Meiyu, but also with the spatial distribution and intensity of precipitation in the MLYR. It is found that when the westerly jet core in the upper troposphere is located over the WP and is coupled with an 850-hPa southwesterly jet, heavy precipitation accompanied by strong convergence and plenty supply of water vapor, occurs in the lower reaches of the Yangtze River. If the 200-hPa westerly jet core is located over the EAC, and without an 850-hPa southwesterly jet, only weak precipitation occurs in the MLYR. Therefore, the longitudinal location of the EAWJ core plays an important role in determining the upper- to lower-level circulation structure and the spatial distribution of heavy precipitation in the MLYR during the Meiyu period.

Key words: East Asian westerly jet (EAWJ), zonal location change of the westerly jet core, precipitation distribution, Meiyu

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1. Introduction

In the Northern Hemisphere, the East Asian westerly jet (EAWJ) is a strong system, and it has a heavy influence on the regional weather and climate. The location and intensity changes of the EAWJ are intimately related to not only the robust seasonal evolutions of the atmospheric circulation over East Asia, but also the starting and ending dates of rainy seasons in eastern China, i.e., Meiyu over the middle-lower reaches of the Yangtze River (MLYR hereafter) and the rainy season over northern China (Ye et al., 1958; Li et al., 2004; Liao et al., 2004). Previous studies have suggested that the southern branch of the EAWJ moving southward or back to the north marked the change of season. In winter, if the southern branch of the EAWJ was anomalously stronger (weaker), so would be the precipitation in spring in southern China and in summer in northern China (Liang and Liu, 1994). Based on observations and general circulation model simulations, Liang and Wang (1998) found that the upper troposphere westerly jet had an important

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effect on the East Asian monsoon precipitation. Meiyu is a significant climate phenomenon with persistent rainfall over the MLYR in late spring and early summer, called Changma over the southern Korean Peninsula and Baiu over South Japan, respectively. Meiyu is a unique climate feature in the East Asian monsoon region, and its onset is closely related to the seasonal variation of the atmospheric circulation over East Asia, particularly to the summer monsoon (Zhou, 2006). The Meiyu period starts earlier (later) if the seasonal transition of the atmospheric circulation kicks off earlier (later) from winter to summer (Tao et al., 1958). Two northward shifts of the EAWJ correspond to the starting and ending dates of Meiyu in June and July. If the atmospheric circulation patterns over East Asia and the western Pacific in July were similar to the climatic patterns in June (August), the seasonal transition of the atmospheric circulation would delay (advance), corresponding to an anomalously long (short) Meiyu period in the MLYR (Liao et al., 2006). It was found that the westerly index was intimately correlated with the interannual variation of Meiyu, per the variation of the 500-hPa zonal wind in the Northern Hemisphere (Dong et al., 1987; Xu Haiming et al., 2001). Therefore, the changes in the location and intensity of the EAWJ play an important role in both the starting/ending dates of Meiyu and the spatial distribution of precipitation during the Meiyu period in the MLYR.

Previous studies are mainly concentrated on the latitudinal (south-north) location anomaly of the EAWJ in association with the Meiyu onset and precipitation distribution during this period. It has been proved that there are both latitudinal and longitudinal shifts of the EAWJ in June and July by Zhang et al. (2006), Kuang (2006), and Kuang et al. (2006a,b). But the effects of longitudinal location and intensity changes of the EAWJ on both the Meiyu onset and precipitation distribution in the MLYR are still unknown. The aim of the paper is to identify the longitudinal location characteristics of the EAWJ and its impact on the spatial distribution and total amount of the Meiyu precipitation in the MLYR by using observations and the NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) reanalysis data.

2. Data

The NCEP/NCAR pentad mean reanalysis data from 1958 to 1997 are used in this paper. The selected meteorological variables include zonal wind, air temperature, vertical velocity, and specific humidity. The horizontal resolution of all variables is $2.5^\circ \times 2.5^\circ$, with 12 levels in the vertical for zonal wind and air temperature, 17 levels for vertical velocity, and 8 levels for specific humidity, respectively. The observed daily rainfall data at 714 stations of China during 1951–2002 are obtained from the China National Meteorological Information Center. The quality control of data is performed using the homogenization method. A Cressman objective analysis is done to obtain gridded data. The starting and ending dates of Meiyu in the MLYR for 1885–2000 are obtained from Xu Qun et al. (2001).

3. The zonal distribution of the EAWJ associated with Meiyu

The 200-hPa zonal winds have been averaged in several pentad periods associated with the starting and ending pentads of Meiyu (Xu Qun et al., 2001) from 1958 to 1997 (Fig. 1). The composite results are statistically significant at the 0.01 level through the student *t*-test. From Fig. 1, it is seen that the upper troposphere westerly jet appears over the East Asian continent (EAC) with sustained strength and over the western Pacific (WP) with gradually reduced intensity. The jet core is defined as the region in which the zonal wind is larger than 35 m s^{-1}. The jet core over the WP splits into two parts and disappears by the ending pentad of Meiyu. The east-west patterns of the EAWJ are divided roughly by the land-sea distribution over East Asia, i.e., there occurs the obvious differences of sea-land distributions of the EAWJ.

At the first pentad before the starting of Meiyu, the EAWJ almost covers 30°E–180° and has only one

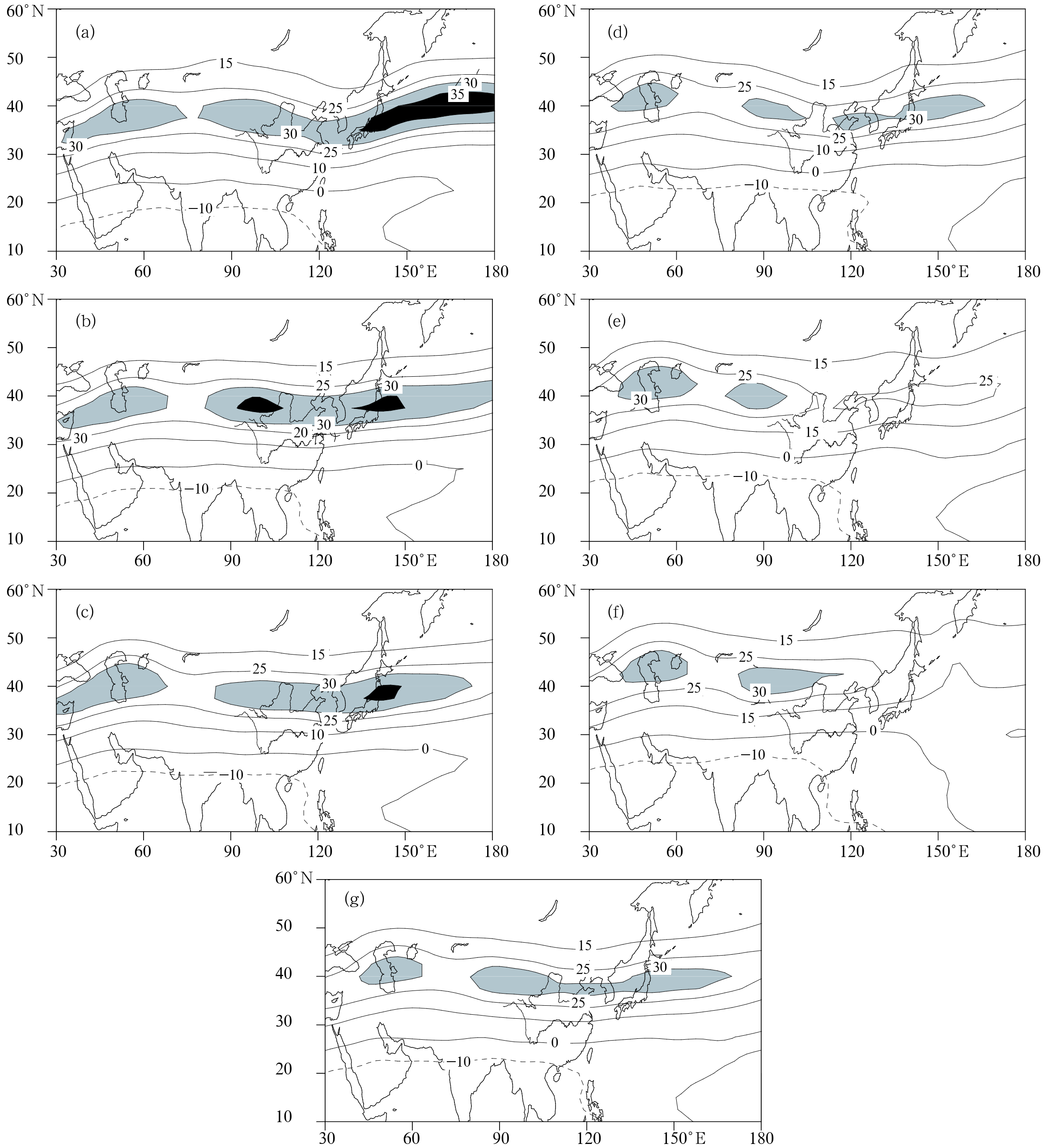

Fig. 1. Composite distributions of the 200-hPa zonal wind (m s^{-1}) during the Meiyu period over 1958–1997 (shadings: $u \geqslant 30$ m s^{-1}) for (a) the first pentad before the starting of Meiyu, (b) the Meiyu starting pentad, (c) the first pentad after the starting of Meiyu, (d) the first pentad before the ending of Meiyu, (e) the Meiyu ending pentad, (f) the first pentad after the ending of Meiyu, and (g) the Meiyu period.

jet core located over the WP (Fig. 1a). At that time, the westerly jet over the WP, is dominant, which is called the western Pacific pattern of the westerly jet. The westerly jet core appears over the EAC at the Meiyu onset, and the core over the WP weakens remarkably (Fig. 1b). During the Meiyu period, the westerly jet located over the WP gradually weakens and disappears, but the other jet core located over the EAC quickly shifts northward to the Yellow River, and becomes dominant. This is called the EAC pattern of the westerly jet. The MLYR is still far away from the westerly jet core when the mid-summer season comes

(Fig. 1f). The westerly jet has two cores during the Meiyu period: one is located over the WP, and the other is over the EAC (Fig. 1g). The location of the MLYR relative to the EAWJ has undergone three changes: firstly, the MLYR is at the westerly jet entrance region over the WP; secondly, it is in the south sides of two westerly jet cores over East Asia; finally, it is in the farther south from the EAWJ. This is caused by the changes of the longitudinal location and intensity of the westerly jet. The EAWJ is a major influence on precipitation in eastern China (Gao, 1952). The heavy precipitation is generally located underneath between the south of the westerly jet entrance and the north of the southwesterly jet. However, precipitation is very strong during the Meiyu period, especially from durative rainstorms (Zhou, 2006). Therefore, the longitudinal location and intensity changes of the 200-hPa westerly jet are strongly associated with the temporal-spatial distribution and intensity of precipitation in the MLYR during the Meiyu period.

3.1 The 200-hPa westerly jet core and the starting and ending dates of Meiyu

According to Zhang et al. (2006), the northward shifting of the EAWJ in summer are often accompanied with its westward shifting. Does the longitudinal location change of EAWJ associate with the starting and ending dates of Meiyu? Generally, the Meiyu starts in June and ends in July. Two key regions are selected for this study: the Meiyu starting key region of 37°–40°N, 100°–120°E and the Meiyu ending key region of 40°–43°N, 80°–100°E, where the 200-hPa westerly jet core appears frequently in June and July, respectively. When the 200-hPa westerly jet core is located over the starting (ending) key region with regional mean zonal winds larger than 30 m s^{-1}, the starting (ending) pentads of Meiyu are defined at this time. The starting and ending pentads of Meiyu by our definition are nearly consistent with those defined by Xu Qun et al. (2001). The correlation coefficients of the annual starting and ending dates of Meiyu determined by jet locations and observations (Xu Qun et al., 2001) are 0.76 and 0.81, passing the 90% confidence level, respectively. Therefore, it is reasonable to infer that the location and intensity variations of the 200-hPa westerly jet in the two key regions are indicative of the Meiyu period.

3.2 Vertical structure

The profiles of mean zonal winds, averaged over both 37°–40°N and 40°–43°N, are demonstrated in Fig. 3. At the first pentad before the starting of Meiyu, there exist three 200-hPa westerly jet cores over the Northern Hemisphere in Fig. 3a: two are located over the EAC, namely the Iranian and Tibetan plateaus, and another over the WP. The intensity of the latter ($u \geqslant 35$ m s^{-1}) is very strong and extends downward to nearby 300 hPa. At the Meiyu starting pentad, the westerly jet core over the WP shifts westward by 10–15 longitude degrees, and its intensity weakens notably. It joins the westerly jet over the Tibetan Plateau with increasing intensity over the WP. At the first pentad before the ending of Meiyu, three westerly jet cores remarkably weaken, compared with

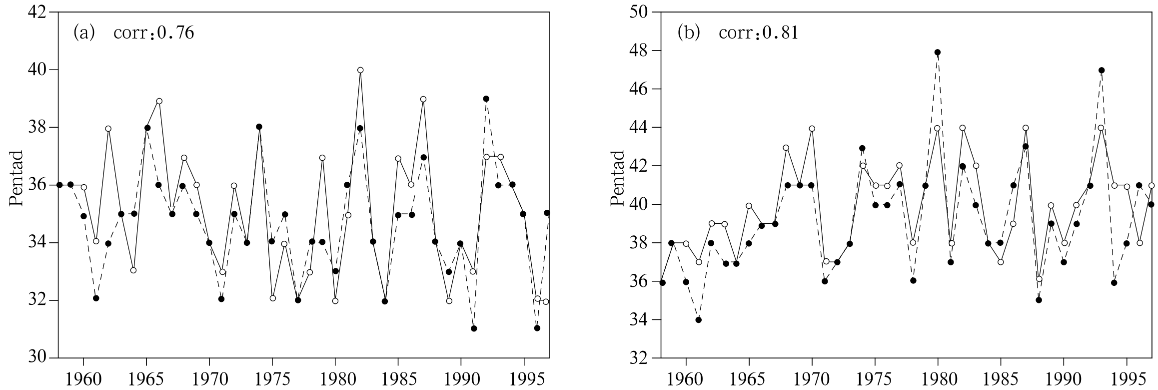

Fig. 2. Interannual variation of the (a) starting and (b) ending dates of Meiyu determined by jet locations (solid line with ○) and given by Xu Qun et al. (2001) (dashed line with ●), respectively.

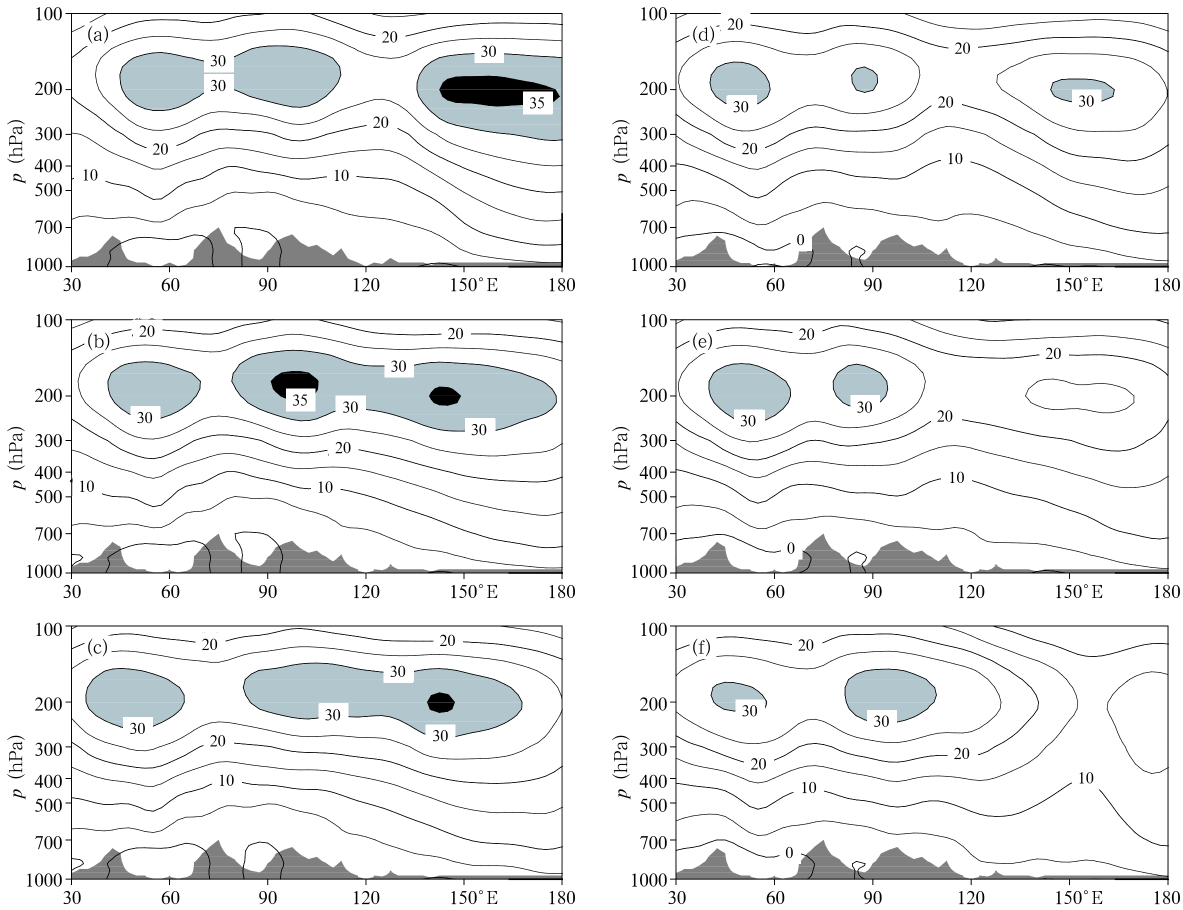

Fig. 3. Longitude-height cross-sections of the composite zonal wind (shadings: $u \geqslant 30$ m s^{-1}) during the Meiyu period over 1958–1997 for (a) the first pentad before the starting of Meiyu, (b) the Meiyu starting pentad, (c) the first pentad after the starting of Meiyu, (d) the first pentad before the ending of Meiyu, (e) the Meiyu ending pentad, and (f) the first pentad after the ending of Meiyu. The zonal wind in (a, b, c) is averaged over 37°–40°N, and that in (d, e, f) over 40°–43°N.

that at the first pented before the starting pentad of Meiyu. At the ending of Meiyu, the 200-hPa westerly jet disappears, and the westerly jets over the Iranian and Tibetan plateaus strengthen somewhat. It is known from the analysis above that at the start of Meiyu, the EAWJ has a notable characteristic of westward shifting. The westerly jet over the WP weakens gradually and disappears untill the Meiyu ending. These suggest that the zonal distribution of the EAWJ has an obvious sea-land pattern.

3.3 Frequency distribution of the EAWJ core

The frequency occurrence distributions of the EAWJ located over the region of 20°–50°N, 81°–170°E during the Meiyu period of 1958–1997 is divided into sea and land patterns by the borderline of 120°E. It is seen in Fig. 4a that the EAWJ core occurs frequently to the east of 140°E two pentads before the Meiyu onset. The EAWJ core is mainly located over the WP with the ratio of the occurrences over ocean vs. the total occurrences being of 62/80. During the Meiyu period, the area with large occurrence numbers oscillates between 140°–170°E and 80°–105°E, and the number of occurrence over sea to that over land is almost the same, namely 119 and 99, respectively. After Meiyu is ended, the EAWJ core moves to the west of 140°E, and the ratio of the occurrences over land to the total is 59/80. Furthermore, based on the zonal wind data for 1958–1997 over the key regionc of 20°–50°N, 80°–170°E, the frequencies on the longitude

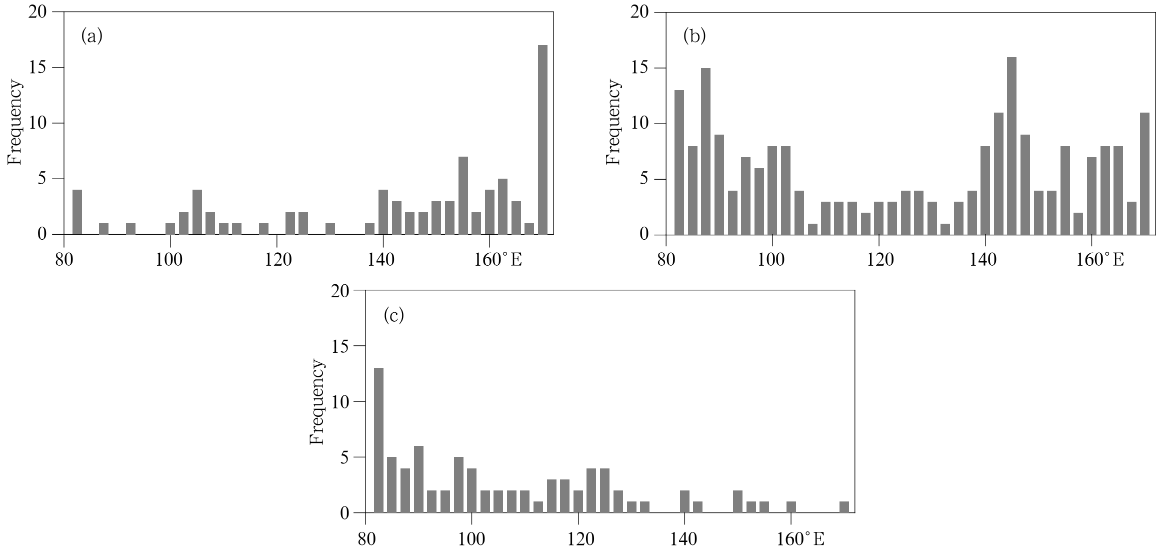

Fig. 4. Occurrence frequency of the westerly jet core in the region of 20°–50°N, 81°–170°E during the Meiyu period in 1958–1997 for (a) two pentads before the starting of Meiyu, (b) the Meiyu period, and (c) two pentads after the ending of Meiyu.

and latitude locations of the EAWJ core and their variability are calculated during the Meiyu period. The results indicate that the longitudinal variability is much larger than the latitudinal variability. It can be inferred that the position change of the EAWJ is more significant in the zonal than in the meridional direction during the Meiyu period.

3.4 Spatial distribution of precipitation

The statistical analyses show that there are two obvious different spatial patterns of the EAWJ during the Meiyu period: the WP pattern (sea pattern) and the EAC pattern (land pattern). The spatial distributions of the 200-hPa mean zonal wind and the mean total precipitation amount of Meiyu in 1958–1997 are given in Fig. 5. When the 200-hPa westerly jet core covering a large area is located over the WP, it is stronger than over the EAC. The MLYR is just located underneath the south of the upper westerly jet entrance, where heavy precipitation occurs and the rainfall amount is more than 60 mm pentad^{-1} as in Fig. 5c. While the westerly jet core is located over the EAC, the MLYR located underneath the south of the exit of the westerly jet receives weak precipitation (Fig. 5d). Therefore, there is a good correlation between the spatial distribution and intensity of heavy precipitation in the MLYR and the east-west (sea-land) distribution of the EAWJ during the Meiyu period.

4. A case study in 1980

A catastrophic flooding disaster happened in the MLYR in 1980. Four heavy rainfall events appeared in the MLYR during the 43-day Meiyu period. The sea-land distribution characteristic of the 200-hPa westerly jet (Figs. 5a, 5b) was very similar to the spatial distribution of the heavy precipitation (Figs. 5c, 5d) in 1980. The case in 1980 is an example for analyzing how the sea-land distribution of the 200-hPa westerly jet impacts on the spatial distribution and intensity of precipitation in the MLYR. When the upper westerly jet core was located at 37.5°N, 150°E over the WP during the Meiyu period, its intensity was strong and the zonal wind value was larger than 40 m s^{-1} in Fig. 6a. Heavy precipitation appeared in the lower reaches of the Yangtze River with the rainfall amount over 90 mm pentad^{-1}. Less heavy precipitation occurred in the middle reaches of the Yangtze River (Fig. 6c). When the westerly jet core was located over the EAC, its intensity was weak and the zonal wind value was about 35 m s^{-1} (Fig. 6b). Heavy precipitation occurred in the middle-upper reaches of the Yangtze

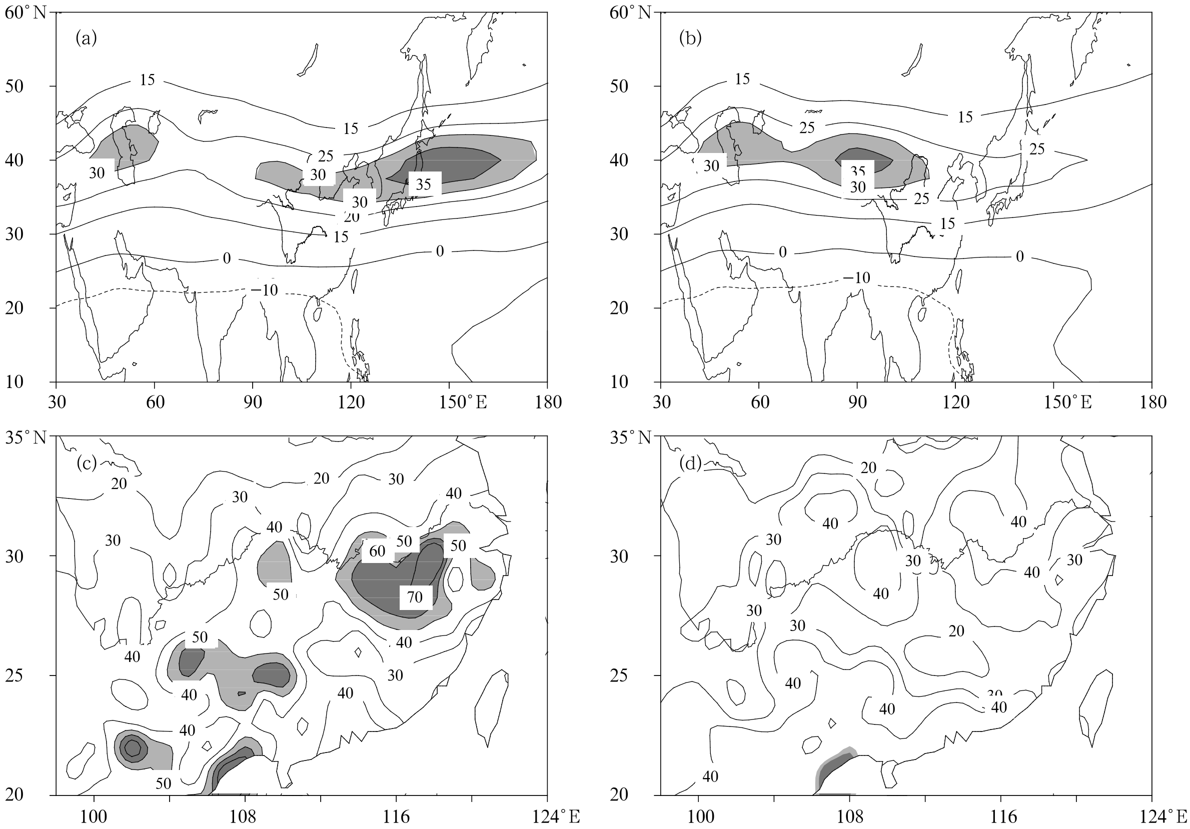

Fig. 5. Composite distributions of the 200-hPa zonal wind (shadings: $u \geqslant 30$ m s^{-1}) for (a) WP jet pattern, (b) EAC jet pattern, and (c, d) their corresponding precipitation distributions (shadings: rainfall $\geqslant$50 mm pentad^{-1}) during the Meiyu period in 1958–1997.

River with precipitation intensity larger than 70 mm pentad^{-1}. Weak precipitation appeared in the lower reaches of the Yangtze River (Fig. 6d).

The Meiyu period is usually featured with the durative overcast rains and storm rainfall. The sufficient supply of water vapor and the strong vertical motions are the necessary conditions for the heavy precipitation. In addition, the amount of the water vapor directly affects the intensity of the precipitation. The influence of the location and intensity differences of the EAWJ on the distributions of water vapor, the convergence of wind, and the upward motion is of great importance. Therefore, analysis of water vapor, vertical motion, and their spatial distribution south of the westerly jet contributes to understanding how the location and intensity differences of the EAWJ impact on the spatial distribution and intensity of precipitation during the Meiyu period.

4.1 Water vapor distribution

Figure 7 shows distributions of the specific humidity, 850-hPa water vapor divergence and flux for the WP jet pattern and the EAC jet pattern during the Meiyu period, respectively. From Fig. 7a, when the westerly jet was located over the WP, the area south of the MLYR received sufficient water vapor supply, with specific humidity larger than 12 g kg^{-1}, and the area extended to southern Japan. It was known from the shaded specific humidity areas that water vapor mainly came from the South China Sea and concentrated in the southern Yangtze River. This indicted that if the westerly jet core was located over the sea, the MLYR had sufficient water vapor supplied. When the westerly jet was located over the EAC, the larger specific humidity area was anomalously to the west, and especially weaker in the lower reaches of the

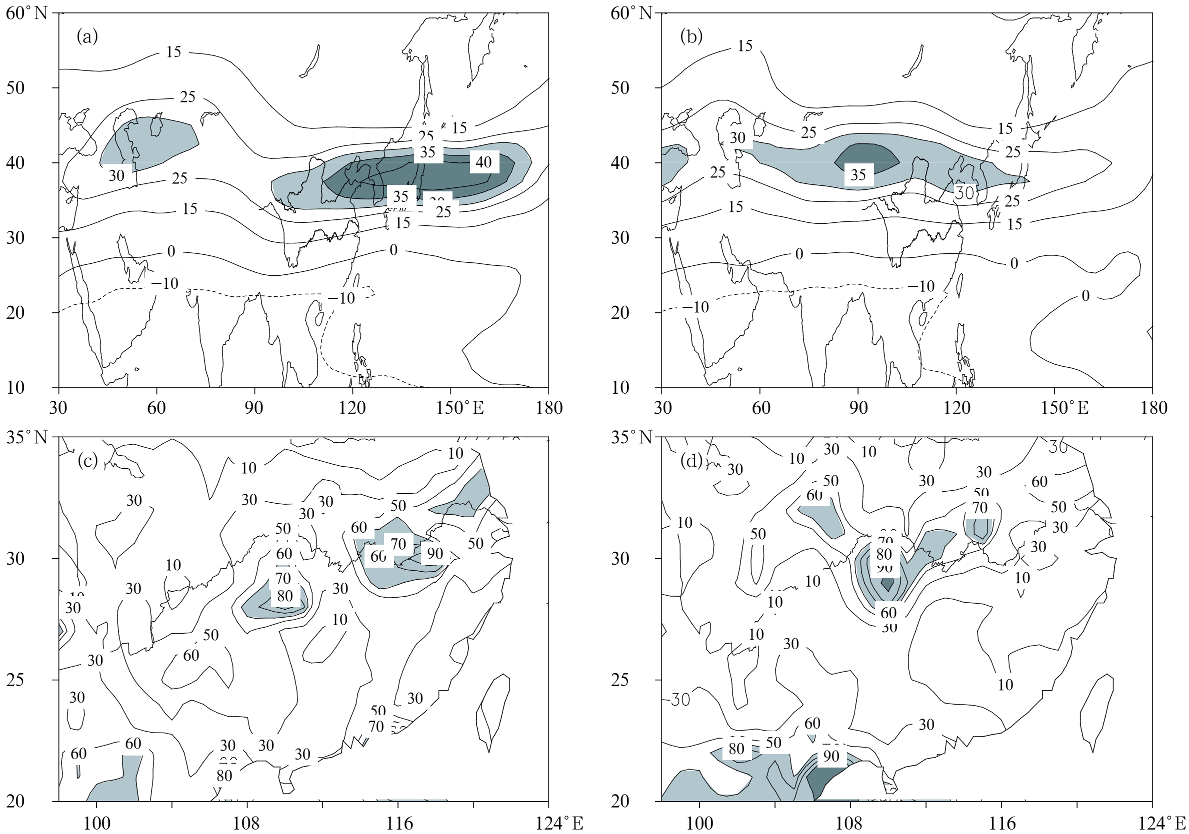

Fig. 6. As in Fig. 5, but for 1980.

Yangtze River (Fig. 7b). Seen from the spatial distribution of the water vapor flux, the water vapor transport by the westerly jet located over the WP was anomalously farther north than that over the EAC, and it extended along the MLYR (Fig. 7c), where the water vapor divergence was stronger in contrast with the 850-hPa water vapor flux convergence (Fig. 7e). When the westerly jet was located over the EAC, the water vapor convergence was stronger and its gradient was very strong in the middle reaches of the Yangtze River, where heavy precipitation appeared (Fig. 6d). In summary, when the westerly jet was located over the WP, water vapor supply was sufficient and convergence and rising motion were strong in the MLYR, which all contributed to the spiral appearance of the heavy precipitation (Fig. 6c).

4.2 The coupling of the upper and lower jets

The ageostrophic wind equation (Shou et al., 2003) is:

$$\boldsymbol{V}_{\rm a} = \frac{1}{f}\boldsymbol{k}\times(\frac{\partial \boldsymbol{V}_{\rm g}}{\partial t} + \boldsymbol{V}_{\rm g}\cdot\nabla\boldsymbol{V}_{\rm g}),$$

where $\boldsymbol{V}_{\rm a}$ and $\boldsymbol{V}_{\rm g}$ are the ageostrophic and geostrophic winds, respectively. The parameter $\boldsymbol{V}_{\rm a}$, which points to the anticyclone (high pressure) of the westerly jet, is generated by $\dfrac{\partial \boldsymbol{V}_{\rm g}}{\partial t}$. The entrance of the westerly jet has anomalously south ageostrophic wind. A circulation is formed in the y-z coordinates, which, together with the direct circulation generated by the earth rotation, causes the convergence and upward motion to strengthen in the entrance of the westerly jet. If the water vapor is sufficient, strong convection will happen and heavy precipitation will appear in this region. Therefore, the ageostrophic wind south of the westerly jet entrance is conducive to the occurrence of heavy precipitation.

The spatial distributions of the upper- and lower-level jets with sea-land patterns are demonstrated in Fig. 8. When the westerly jet was located over the WP, the lower reaches of the Yangtze River was the region where the upper- and lower-level jets couple with each other. Underneath the entrance region of the westerly jet, the axis of the 850-hPa southwesterly

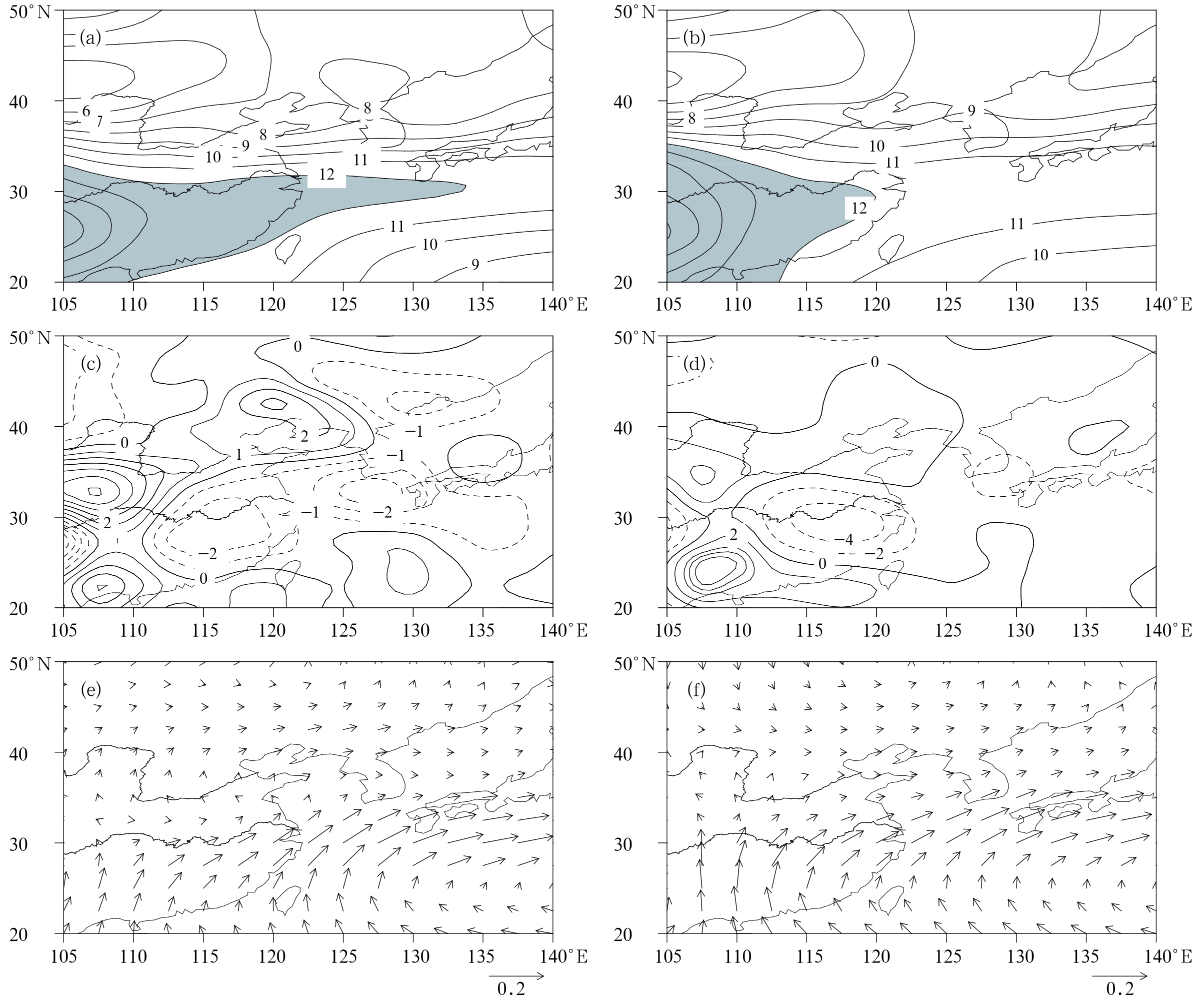

Fig. 7. The 850-hPa specific humidity (shadings > 12 g kg^{-1}), water vapor flux divergence (10^{-8} g s^{-1} cm^{-2} hPa^{-1}) and wind vector (g s^{-1} cm^{-1} hPa^{-1}) distributions for the WP jet pattern (a, c, e) and the EAC jet pattern (b, d, f) during the Meiyu period in 1980.

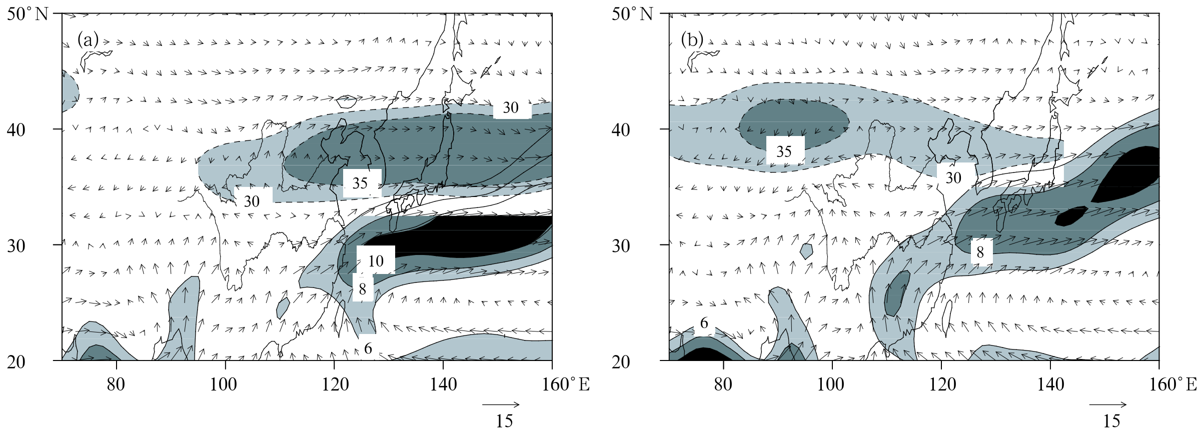

Fig. 8. The 850-hPa wind vector (m s^{-1}) distributions for the WP jet pattern (a) and EAC jet pattern (b) during the Meiyu period in 1980. Shaded areas with dashed (solid) lines indicate the 200-hPa upper-level (850-hPa low-level) jet.

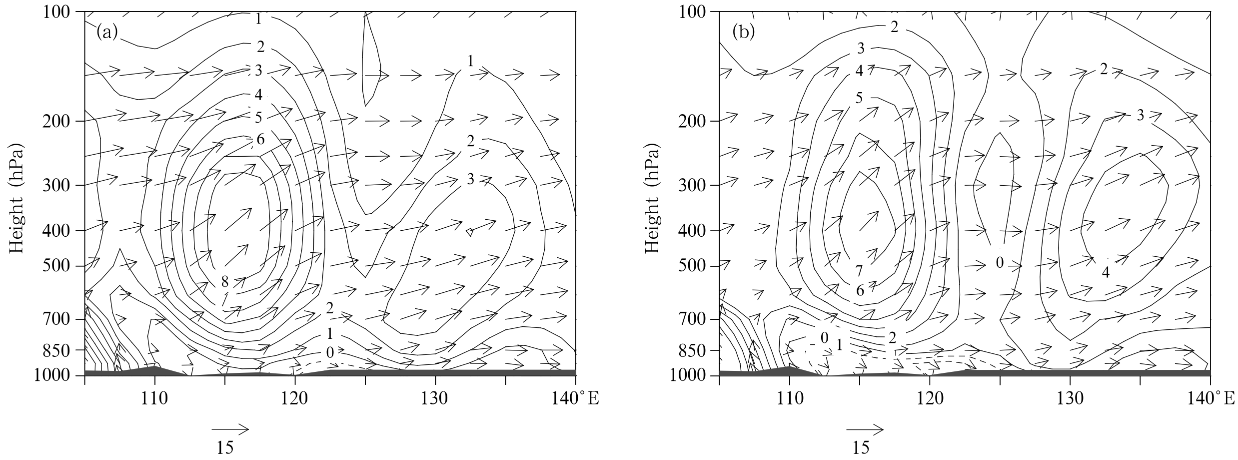

Fig. 9. Longitude-height cross-sections of the vertical circulation averaged over 26°–33°N for the WP jet pattern (a) and the EAC jet pattern (b) during the Meiyu period in 1980. Vertical velocities are multiplied by 100 (unit: 10^{-2} m s^{-1}).

jet is roughly parallel to that of the 200-hPa westerly jet (Fig. 8a). Due to the ageostrophic wind, a transverse circulation, ascending on the right side and descending on the left, exits on the entrance of the westerly jet core. The horizontal flow diverges on the right of the westerly jet. The circulation was formed by the convergence and upward motion, and the other was thermally direct (i.e., descending cold air and rising warm air). The lower reaches of the Yangtze River was just located in the upward motion regions of these circulations. If the water vapor is abundant, the strong convection will happen easily and heavy precipitation occurs (Fig. 6c). When the westerly jet is located over the EAC, the 850-hPa southwesterly jet is located over the WP. Due to the anomalous northward location of the westerly jet and no coupling of the upper- and lower-level jets, weak precipitation occurs in the lower reaches of the Yangtze River. Therefore, the coupling of the upper- and lower-level jets is probably one of the important reasons for the heavy precipitation in the MLYR during the Meiyu period.

Figure 9 shows the longitude-height cross sections of the vertical circulation averaged over 26°–33°N for the WP jet pattern and the EAC jet pattern during the Meiyu period in 1980. When the westerly jet is located over the WP, the convergence and rising motion are very strong at 120°E between 700 and 300 hPa. The convection is quite vigorous in this region. The precipitation is anomalously eastward and its intensity is anomalously strong. When the westerly jet is located over the EAC (Fig. 9b), the convergence and upward motion are located in about 110°E, and is anomalously westward of more than 10°. The rising motion is anomalously weak and causes the occurrence of weak precipitation in the region. The upward motion in the entrance region of the westerly jet is obviously stronger than that in the exit region. The strong rising motion below south of the entrance region of the upper westerly jet is a necessary condition for convective rainfall. This contributes to the heavy rainfall in this region together with the abundant water vapor supply.

5. Conclusions

The intensity of the westerly jet over the EAC maintains during the Meiyu period. The core of the westerly jet over the WP splits up with its intensity reduced and it disappears by the end of Meiyu. The east-west patterns of the EAWJ are divided roughly by the coastline over East Asia, i.e., there occurs an obvious difference in the EAWJ distribution over sea and land. The east-west (sea-land) pattern of the EAWJ impacts on the spatial distribution and intensity of the precipitation in the MLYR during the Meiyu period. When the westerly jet is located over the

WP, remarkably heavy precipitation occurs in the lower reaches of the Yangtze River, and the entrance of the westerly jet is coupled with an 850-hPa southwesterly jet, where the convergence and upward motion are quite strong. Heavy precipitation occurs in the lower reaches of the Yangtze River due also to sufficient water vapor supply. This indicates that when the westerly jet is located over the WP, the upper-level circulation facilitated by the coupling of the upper- and lower-level jets is beneficial to the strong precipitation in the MLYR during the Meiyu period.

Through analysis of the location and intensity changes of the EAWJ during the Meiyu period, this paper has proved that there are notable differences in the east-west location or the sea-land pattern of the EAWJ core, which affect the spatial distribution and intensity of precipitation in the Yangtze River Valley, especially the lower reaches. However, issues about the reasons for this influence, and the interannual variations of the longitudinal location and intensity changes of the EAWJ remain to be investigated in the future.

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